

## COSMIC-RAY SPECTRUM AND COMPOSITION WITH THE ICECUBE OBSERVATORY

ALESSIO TAMBURRO\* FOR THE ICECUBE COLLABORATION

*Bartol Research Institute and Department of Physics and Astronomy  
University of Delaware, Newark, DE 19716, USA*

*\*E-mail: tamburro@udel.edu*

This paper reports on recent results from measurements of energy spectrum and nuclear composition of galactic cosmic rays performed with the IceCube Observatory at the South Pole in the energy range between about 300 TeV and 1 EeV.

**Keywords:** Cosmic rays; energy spectrum; nuclear composition.

### 1. Introduction

Most galactic cosmic rays are believed to be accelerated in the blast waves of nearby supernova remnants, reaching a maximum energy that scales with the charge of the nucleus. The heaviest elements can gain up to about  $10^{18}$  eV. The signatures of these sources are the gradual steepening of the cosmic-ray flux at a few  $10^{15}$  eV, called the *knee*, and possibly more structures at higher energies.

The IceCube Observatory<sup>1</sup> (Fig. 1(a)) is a three-dimensional cosmic-ray air shower detector measuring primary cosmic particles with energy  $E$  between about  $3 \cdot 10^{14}$  eV and  $10^{18}$  eV. The observatory has been in operation since May 2011

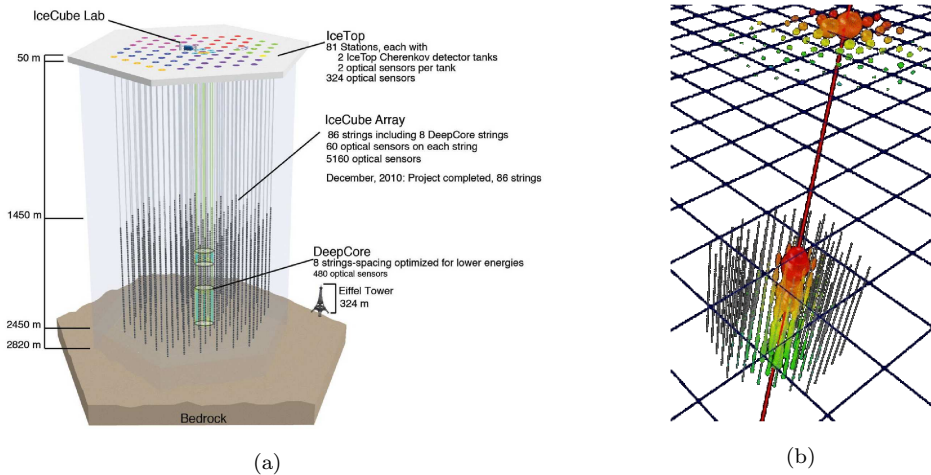


Fig. 1. (a) Sketch of the IceCube Observatory. IceCube in its 2006-07 configuration is shown in red and termed as IT26/IC22 (26 IceTop stations/22 in-ice strings). Other configurations are IT40/IC40 (2007-08) in green, IT59/IC59 (2008-09) in violet, IT73/IC79 (2009-10) in blue, and IT81/IC86 (2010-11) in yellow. (b) Coincident event recorded in 2010 (IT73/IC79). Colored spheres indicate DOM signals (the earliest ones being in red) with strength proportional to the radius.

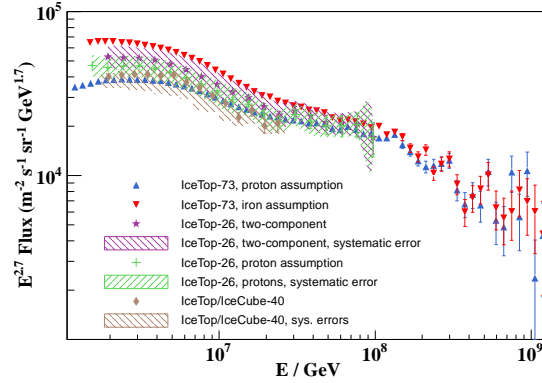


Fig. 2. Energy spectra obtained with data of IceTop running in different configurations as labeled.

with 86 strings between 1.45 and 2.45 km below the surface. Each string carries 60 digital optical modules<sup>2</sup> (DOMs) which include photomultipliers and readout electronics. Near the top of each string (2835 m altitude, atmospheric depth of about 680 g/cm<sup>2</sup>), 81 pairs (stations) of cylindrical Cherenkov tanks cover about 1 km<sup>2</sup> and are part of the surface component of IceCube, named IceTop.<sup>3</sup> Each tank contains two standard IceCube DOMs and samples low-energy photons, electrons, and muons from air showers. The deep detectors measure the signal of penetrating muons (more than about 500 GeV) from the early stage of shower development.

In Fig. 1(b) an event seen in coincidence by both the surface and the deep detectors (coincident event) is shown. The effective area of IceCube for coincident events is  $A \approx 0.15$  km<sup>2</sup>sr (0.4 km<sup>2</sup>sr for IceTop alone). The maximum energy above which the intensity is too low to obtain enough events for analysis is about 1 EeV.

## 2. Primary Energy Spectrum and Nuclear Composition

The position of IceTop at the high altitude of the South Pole makes it possible to sample secondaries near the shower maximum, thus reducing the effects of fluctuations. The energy resolution is 0.1 or less in units of  $\log_{10}(E/\text{GeV})$  above about 1 PeV (0.05 above 10 PeV). The first analysis to determine the all-particle energy spectrum<sup>4</sup> (Fig. 2) was based on data of IT26 (area of 0.094 km<sup>2</sup>, June to October 2007). Assuming mixed composition (H and Fe only), the knee is measured at about 4.3 PeV and the spectral index above the knee is about -3.1. An indication of a flattening of the spectrum above 22 PeV is also observed with a spectral index changing to about -2.9. A preliminary measurement of the IT73 spectrum was obtained by analyzing 11 months of data (June 2009 to May 2010). The statistics is nearly  $4 \cdot 10^7$  events. Of these events, about 200 are found above about 200 PeV.

A measurement of the primary mass composition (Fig. 3) was performed with one month of data<sup>5</sup> of IT40/IC40. A neural network was trained with Monte Carlo

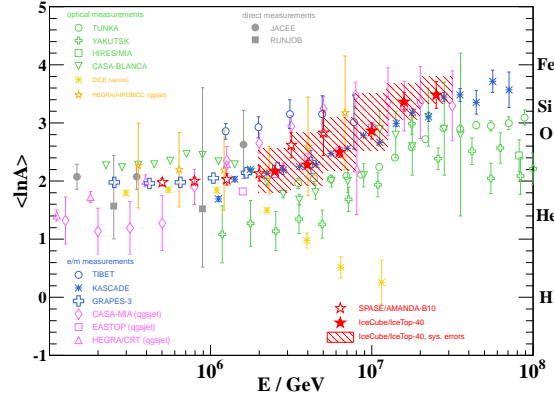


Fig. 3. The mean logarithmic mass  $\langle \ln A \rangle$  vs primary energy adapted from Ref.5. The result indicates a strong increase in mass through the knee although the systematic uncertainties can greatly affect the measured composition in terms of absolute value of  $\langle \ln A \rangle$ .

simulations of 5 primaries (H, He, O, Si, Fe). Measurements of  $e/\gamma$  component of air showers at the surface and  $\mu$  component in the ice are used to “teach” the network how to find the best fit to  $E$  and mass.

### 3. Conclusions

The IceCube Observatory is currently taking data in the second year after its completion. Based on data of the detector in earlier stages of its deployment, events seen in coincidence by both the surface component and in-ice detectors have been analyzed to investigate the mass composition of cosmic rays. IceTop event analysis resulted in measurements of the cosmic-ray energy spectrum. The results are in line with those of other experiments but IceCube has the potential to yield high precision for energy and mass spectrum from below the knee to about 1 EeV.

### Acknowledgments

I am grateful to T. Gaisser, H. Kolanoski, and T. Stanev for discussions. This research is supported in part by the U.S. National Science Foundation Grant NSF-ANT-0856253.

### References

1. A. Achterberg *et al.* [IceCube Collaboration], *Astropart. Phys.* **26**, 155 (2006).
2. R. Abbasi *et al.* [IceCube Collaboration], *Nucl. Instrum. Methods A* **601**, 294 (2009).
3. R. Abbasi *et al.* [IceCube Collaboration], *arXiv* 1207.6326 (2012).
4. R. Abbasi *et al.* [IceCube Collaboration], *arXiv* 1202.3039 (2012).
5. R. Abbasi *et al.* [IceCube Collaboration], *arXiv* 1207.3455 (2012).